Final Progress Report

For period May 1, 2002 – November 30, 2006

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March 14, 2007

By Professor Mikhail Lukin, PI

"Development of a Quantum Repeater for Long-Distance Quantum Communication Using Photonic Information Storage"

Office of Naval Research

Award Number N00014-02-1-0599

Table of Contents

Statement of Problem Studied

Abstract

In this project, we have carried out the pioneering work for long-distance quantum communication using atomic ensembles for photon-state storage and for implementation of quantum repeaters. This work was followed by many groups and is now considered as one of the most promising approaches to overcoming photon losses in long-distance quantum communication. Specific highlights include theoretical proposals for quantum repeaters based on atomic ensembles (Nature, 414, 413, 2001), atom-atom correlations mediated by dark-state polaritons (Phys.Rev.Lett., 88, 243602, 2002), generation of stationary pulses of light (Phys.Rev.Lett, 89, 143602, 2002); experimental demonstrations of atomic memory for correlated photon states (Science, 301, 196, 2003), stationary pulses of light (Nature 426, 638, 2003), shaping quantum pulses via atomic memory (Phys.Rev.Lett. 93, 233602, 2004)), and finally realization of two-node quantum network involving generation and storage of single photon pulses in two remote ensembles (Nature, 438, 837, 2005). Finally, we proposed and analyzed a novel method that uses fixed, minimal physical resources to achieve generation and nested purification of quantum entanglement for quantum communication over arbitrarily long distances. In this method, solid-state single photon emitters with two internal degrees of freedom formed by an electron spin and a nuclear spin are used to build intermediate nodes in a quantum channel (Phys.Rev.Lett. 96,070504, 2006). Recently, we have experimentally demonstrated such a node using Nitrogen-Vacancy centers in room temperature diamond lattice (submitted to Science, 2007).

Technical Section

2001-2002

We have carried out a detailed theoretical analysis of a photon state trapping technique, and in addition, studied theoretically, the basic properties of form-stable coupled excitations of light and matter ("dark-state polaritons") associated with the propagation of quantum fields in Electromagnetically Induced Transparency (EIT) and their application as quantum memory for light. [Phys.Rev.A, 65, 022314 (2002)].

Experimentally, the phase coherence and control for the "light storage" technique has been demonstrated. Specifically, we employed this technique to bring the group velocity of a light pulse to zero, thereby mapping the photonic information into an ensemble spin coherence in warm Rb vapor. We then applied a pulsed magnetic field to vary the phase of the atomic spin excitations and map the altered information back into light using dynamic EIT. We detected the resultant optical phase shift in an interferometric measurement, thus confirming that dynamic EIT preserves phase coherence. [Phys.Rev.A, 65, 031802 (2002)]

We have proposed and theoretically analyzed a technique to induce effective interactions between the atoms in metastable states. This technique is based on Raman scattering into an optical mode propagating with a slow group velocity. The resulting excitation corresponds to the creation of spin-flipped atomic pairs in a way that is analogous to

correlated photon emission in optical parametric amplifier. The technique can be used for fast generation of entangled atomic ensembles, spin squeezing and applications in quantum information processing. [Phys.Rev.Lett., 88, 243602 (2002); Phys.Rev.A, 65, 053819 (2002)]

Our project has brought forth the opportunity to publish a popular article describing the physics of "light stopping" for the non-technical audience with general science and engineering background [Optics and Photonics News, p.51, May (2002)]

2002-2003
We developed a new experimental setup to demonstrate and study storage of quantum-mechanically correlated photon states in atomic ensembles. A new laboratory dedicated to theses studies has been built and is now operational at the Harvard Physics Department. We have developed and implemented several new techniques to study correlations of photon states emerging from atomic memory. These technical developments have been documented in several publications. Using this setup, we experimentally demonstrated emission of two quantum mechanically correlated light pulses with a time delay that is coherently controlled via storage of photonic states in an atomic ensemble. The process is based on Raman scattering, which produces correlated pairs of spin-flipped atoms and Stokes photons, followed by coherent conversion of the atomic states into anti-Stokes photons after a controllable delay. This technique is the basic element of a promising approach for long-distance quantum communication that we proposed last year. The paper describing this major experimental result was published in Science, 301, 196 (2003).

We proposed and analyzed a technique for coherent storage of the polaritons with a non-vanishing photonic component. The technique is based on creating a dynamically controlled photonic bandgap in an atomic ensemble. We showed that dynamic control of such a bandgap can be used to coherently convert a propagating light pulse into a stationary excitation with a non-vanishing photonic component. This can be accomplished with high efficiency and negligible noise even at the level of few-photon quantum fields, thereby facilitating possible applications in quantum nonlinear optics and quantum information. [Phys.Rev.Lett., 89, 143602 (2002)].

2003-2004
We published a review article on our work on the main subject of this project {Rev.Mod.Phys., 75, 457 (2003)].

We described and experimentally demonstrated a novel technique in which light propagating is a medium of Rb atoms is converted into an excitation with localized, stationary electromagnetic energy which can be held and released after a controllable interval. Our method creates pulses of light with stationary envelopes bound to an atomic spin coherence, raising new possibilities for photon state manipulation and non-linear optical processes at low light levels [Nature, 426, 638-641 (2003)].

We carried out proof-of-principle experiments demonstrating a novel approach for generating pulses of light with controllable photon numbers, propagation direction, timing, and pulse shapes. The approach is based on preparation of an atomic ensemble in a state with a desired number of atomic spin excitations, which is later converted into a photon pulse. Spatiotemporal control over the pulses is obtained by exploiting long-lived coherent memory for photon states and Electromagnetically Induced Transparency in an optically dense atomic medium. Using photon counting experiments, we observed Electromagnetically Induced Transparency based generation and shaping of few-photon sub-Poissonian light pulses. [M. D. Eisaman et al, Phys.Rev.Lett, 93, 233602 (2004)]

2005-2006

Using the techniques of Raman scattering, conditional measurements, and EIT-based control of light propagation, we demonstrated experimentally generation of the narrowband, frequency tunable single photons with properties matching those of narrow atomic resonances. High-purity single photons were generated by combining a novel mode-matching geometry with weak Raman excitation [A.Andre Ph.D.Thesis, Harvard University, J.Phys.B 38, S589 (2005)]. In this optimized configuration, high-purity single photon generation was achieved with a room temperature ensemble of Rb atoms.

We performed an experimental demonstration of EIT in a novel, quantum regime using frequency-tunable single-photon pulses. By studying the interaction of single photons produced in one atomic ensemble with another ensemble, we demonstrated that EIT can be used for controlled generation, transmission and delay of single photons with tunable frequency, timing, and bandwidth while preserving their quantum nature. Specifically, we observed enhancement of single photon transmission, single photon-pulse time delay associated with reduced group velocity, and preservation of nonclassical photon statistics as the frequency of the single-photon pulse is scanned through the EIT resonance. Finally, we demonstrated single photon storage using these techniques. For the first time, these experiments also provide a bound on a bandwidth of single photons generated by our source. We found bandwidths of order MHz. [M.Eisaman et al., Nature, 438, 837-841 (2005)]. These results constitute a first experimental realization of a primitive quantum network in which two memory nodes are connected via a single photon transmission.

Motivated by rapid experimental progress towards implementing quantum communication protocols, here we develop a more efficient scheme compatible with active purification of arbitrary errors. Using similar resources as the earlier protocol, our approach intrinsically purifies leakage out of the logical subspace and all errors within the logical subspace, leading to greatly improved performance in the presence of experimental inefficiencies [quant-ph/0609236].

We described a novel method for long distance quantum communication in realistic, lossy photonic channels. We showed that the fixed, minimal physical resources associated with these two degrees of freedom suffice to correct arbitrary errors, making our protocol robust to all realistic sources of decoherence. The method is particularly well suited for implementation using recently-developed solid-state nano-photonic devices. We analyzed this novel method that uses fixed, minimal physical resources to achieve

generation and nested purification of quantum entanglement for quantum communication over arbitrarily long distances, and discussed its implementation using realistic photon emitters and photonic channels. In this method, we used single photon emitters with two internal degrees of freedom formed by an electron spin and a nuclear spin to build intermediate nodes in a quantum channel. State-selective fluorescence was used for probabilistic entanglement generation between electron spins in adjacent nodes. We analyzed in detail several approaches which are applicable to realistic, homogeneously broadened single photon emitters. Furthermore, the coupled electron and nuclear spins can be used to efficiently implement entanglement swapping and purification. We showed that these techniques can be combined to generate high-fidelity entanglement over arbitrarily long distances. We presented a specific protocol that functions in polynomial time and tolerates percent-level errors in entanglement fidelity and local operations. The scheme has the lowest requirements on physical resources of any current scheme for fully fault-tolerant quantum repeaters. [Phys.Rev.A, vol.72, 052330 (2005), Physics Review Letters, vol.96, 070504 (2006)]

We carried out experiments aimed toward a detailed understanding of microwave and optical properties as well as light-matter entanglement generation via Raman scattering in single N-V centers at helium temperatures. Specifically, we designed and constructed a system for spin-photon entanglement measurements, observed long spin coherence times, photon anti-bunching, and narrow stable optical resonance from single N-V centers.

Coherent manipulation of an individual electron spin associated with a nitrogen-vacancy (NV) center in diamond was used to gain insight into its local environment. We showed that this environment is effectively separated into a set of individual, proximal 13C nuclear spins which are coupled coherently to the electron spin, and the remainder of the 13C nuclear spins, which cause the loss of coherence. The proximal nuclear spins could be addressed and coupled individually because of quantum back-action from the electron, which modifies their energy levels and magnetic moments, effectively distinguishing them from the rest of the nuclei. These results open the door to coherent manipulation of individual, isolated nuclear spins in a solid-state environment even at room temperature. [Science, vol. 314, 5797 (2006)]

We described a technique that enables strong, coherent coupling between individual optical emitters and electromagnetic excitations in conducting nanowires. The excitations in the wire are optical plasmons that are localized to sub-wavelength dimensions, and under realistic conditions optical emission can be almost entirely directed into the propagating plasmon modes via a mechanism analogous to cavity quantum electrodynamics. We described an application of this technique involving efficient generation of single photons on demand, in which the plasmon on the nanowire is efficiently out-coupled to a dielectric waveguide. Finally, realistic sources of imperfections were analyzed. [Physics Review Letters, vol. 97, 053002 (2006)]

We investigated a hybrid quantum circuit where ensembles of cold polar molecules serve as long-lived quantum memories and optical interfaces for solid state quantum processors. The quantum memory realized by collective spin states (ensemble qubit) is

coupled to a high-Q stripline cavity via microwave Raman processes. We showed that for convenient trap-surface distances of a few μm, strong coupling between the cavity and ensemble qubit can be achieved. We discussed basic quantum information protocols, including a swap from the cavity photon bus to the molecular quantum memory, and a deterministic two qubit gate. Finally, we investigated coherence properties of molecular ensemble quantum bits. [Phys.Rev.Lett, 97, 033003 (2006)]

We derived an optimal control strategy for storage and retrieval of a photon wavepacket of any given shape in a Lambda-type atomic medium with a limited optical depth. The control is provided by an appropriately shaped classical laser field. We presented a universal physical picture encompassing different pulse-storage techniques ranging from adiabatic reduction of the photon group velocity and pulse-propagation control via off-resonant Raman fields to photon-echo based approaches. When properly optimized, all three approaches yield identical maximum efficiencies, which only depend on the optical depth of the medium. Extending the model to include Doppler broadening, we found the surprising result that at high enough optical depth all atoms contribute coherently as if the medium were homogeneously broadened. [quant-ph/0604037, in press Phys.Rev.Lett (2006)]

Listing of all publications and technical reports supported under the grant

(a) Papers published in peer-reviewed journals

Publications 2002-2006

1. A.V. Gorshkov, A. Andre, M. Fleischhauer, A.S. Sorensen, M.D. Lukin, "Optimal Storage of Photon States in Optically Dense Atomic Media," quant-ph/0604037, in press, Phys.Rev.Lett (2006)

2. D.E. Chang, A.S. Sorensen, P.R. Hemmer, M.D. Lukin, "Quantum Optics with Surface Plasmons," Phys.Rev.Letters, 97, 053002 (2006)

3. L. Childress, J.M. Taylor, A.S. Sorensen, M.D. Lukin, "Fault-tolerant quantum communication based on solid-state photon emitters," Phys.Rev.Lett, 96, 070504 (2006)

4. M.D. Eisaman, M. Fleischhauer, M.D. Lukin, A.S. Zibrov, "Electromagnetically Induced Transparency: towards quantum control of single photons," Optics and Photonics News, vol.17, #1, 22-27 (2006)

5. G. Giedke, J.M. Taylor, D. D'Alessandro, M.D. Lukin, A. Imamoglu, "Quantum Measurement of a Mesoscopic Spin Ensemble," Phys.Rev.A, 74, 032316 (2006)

6. P. Rabl, D.DeMille, J.M. Doyle, M.D. Lukin, R.J. Schoelkopf, P. Zoller, "Hybrid quantum processors: molecular ensembles as quantum memory for solid state circuits," Phys.Rev.Lett, 97, 033003 (2006)

7. F.E. Zimmer, A. Andre, M.D. Lukin, M. Fleischhauer, "Coherent control of stationary light pulses," quant-ph/0602197, Optics Communications, 264, 441 (2006)

8. L. Childress, J.M. Taylor, A.S. Sorensen, M.D. Lukin, "Fault-tolerant quantum repeaters with minimal physical resources, and implementations based on single photon emitters," Phys.Rev.A, **72**, 052330 (2005)

9. A. Andre, M.D. Eisamann, R.L. Walsworth, A.S. Zibrov, M.D. Lukin, "Quantum control of light using electromagnetically induced transparency," Journal of Physics B, 38, S589-S604 (2005)

10. A. Andre, M. Bajcsy, A.S. Zibrov, "Nonlinear optics with stationary pulses of light," Phys.Rev. Lett, 94, 063902/1-4 (2005)

11. M.D. Eisaman, A. Andre, F. Massou, M. Fleischhauer, A.S. Zibrov, M.D. Lukin, "Electromagnetically induced transparency with tunable single-photon pulses," Nature, 438, 837-841 (2005)

12. M.D. Eisaman, M. Fleischhauer, M.D. Lukin, A.S. Zibrov, "Electromagnetically Induced Transparency: towards quantum control of single photons," Optics and Photonics News, vol.1, #3, 129-198 (2005)

13. M. D.Eisaman, L.Childress, A. André, F. Massou, A. S.Zibrov, and M. D.Lukin, "Shaping quantum pulses of light via coherent atomic memory," Phys.Rev.Lett, 93, 233602 (2004)

14. A.S. Sorensen, C.H. van der Wal, L. Childress, M.D. Lukin, "Capacitative coupling of atomic systems to mesoscopic conductors," Phys.Rev.Lett, 92, 063601 (2004)

15. M.D. Lukin, "Colloquium: Trapping and manipulating photon states in atomic ensembles", Rev.Mod.Phys., 75, 457 (2003)

16. C. van der Wal, M.D. Eisaman, A. André, R.L. Walsworth, D.F. Phillips, A.S. Zibrov and M.D. Lukin, "Atomic memory for correlated photon states", Science, 301, 196, (2003)

17. M. Bajcsi, A.S. Zibrov, M.D. Lukin, "Stationary pulses of light in an atomic medium", Nature 426, 638 (2003)

18. C.H. van der Wal, M. D. Eisaman, A. Andre, R. L. Walsworth, D. F. Phillips, A. S. Zibrov and M. D. Lukin, "Atomic memory for correlated photon states," Science, 301, 196; (2003) (published online in Science Express on May 22, 2003)

19. A. Andre, and M.D. Lukin, "Manipulating Light Pulses via Dynamically Controlled Photonic Bandgap," Phys.Rev.Lett., 89, 143602 (2002)

20. Andre, L.M.Duan, and M.D.Lukin, "Coherent Atom Interactions Mediated by Dark-State Polaritons," Phys.Rev.Lett., 88, 243602 (2002)

(b) Papers published in non-peer-reviewed journals or in conference proceedings

1. M.V. Gurudev Dutt, L. Childress, E. Togan, M.J. Taylor, L. Jiang, A.S. Zibrov, P.R. Hemmer, F. Jelesko, J.Wrachtrup, M.D. Lukin, "Quantum control of electron and nuclear spin qubits in the solid-state," Atomic Physics 20, XX International Conference on Atomic Physics, ICAP 2006
2. A. Andre, M. Bajcsy, L. Childress, M.D. Eisaman, F. Massou, A.S. Zibrov, M.D. Lukin, "Quantum control of light using coherent atomic memory," Atomic Physics 19, XIX International Conference on Atomic Physics (2004), L.G. Marcassa, V.S. Bagnato, K. Helmerson, eds. (American Institute of Physics, Melville, New York, 2005)
3. C. van der Wal, M.D. Eisaman, A.S. Zibrov, A. Andrė, D. F. Phillips, R.L. Walsworth, M.D. Lukin, "Towards non-classical light storage via Raman scattering in atomic vapor", Proceedings of SPIE "Noise and Information", vol. 5115, 236 (2003)
4. M.D. Lukin, A. Andre, M. D. Eisaman, M. Hohensee, D. F. Phillips,C. H. van der Wal, R. L. Walsworth, A. S. Zibrov, "Toward Manipulating Quantum Information with Atomic Ensembles," Proceedings of ICAP-2002, page 231, World Scientific (2002)

(c) Papers presented at meetings, but not published in conference proceedings

2006

1. Physics of Quantum Electronics, Salt Lake City, January 2007
2. Slow Light Phase II Review Meeting, Austin, TX, November 2006
3. MURI Center for Photonic Quantum Information Systems Annual Meeting October 2006
4. Stanford University, Stanford Photonics Research Center Workshop, September 2006
5. Penn State Colloquium, College Station, PA, September 2006
6. Optical Society of America, Washington DC, July 2006
7. MURI Review Presentation on Precision Measurement and Gap Protection, by Dr. Ana Maria Rey, Stanford University, Stanford, CA, June 2006

8. 366. WE-Heraeus seminar, "Qubits and Macroscopic Quantum Coherence: From Superconducting Devices to Ultracold Gases," Bad Honnef, Germany, May 2006
9. ICQO 2006: XI International Conference on Quantum Optics, Minsk, Belarus, May 2006
10. Topological Phases and Quantum Computation, Kavli Institute for Theoretical Physics, University of California at Santa Barbara, CA, May 2006
11. Cold Atoms Meet Condensed Matter, Dresden, March 2006
12. Workshop on Decoherence, Entanglement and Information in Complex Systems (DEICS III), Eilat, Israel, February 2006
13. Quantum Computing and many-body systems, Key West, FL, Jan 31-Feb.1, 2006
14. Strong Correlations in Ultra-Cold Fermi Systems, Aspen, CO, January 2006

2005

1. Physics Colloquium, Swiss Federal Institute of Technology, Zurich, Switzerland, December 2005
2. Invited talk at CIAR, the Quantum Information Processing Conference, Quebec City, Canada, December 2005
3. Invited talk at the Darpa Slow Light Review Meeting, Seattle, WA, December 2005
4. Physics Colloquium at ETH, Zurich, Switzerland, December 2005
5. Invited talk at the Symposium on Solid State Quantum Information, University of Massachusetts, Amherst, MA, November 2005
6. Invited talk at the Symposium on Quantum Information, Niels Bohr Institute, Copenhagen, Denmark, November 2005
7. Invited talk at TAMU BEC Symposium, Princeton University, NJ October 2005
8. Seminar at Rutgers, New Brunswick, NJ, October 2005
9. Invited talk at Kochi Summer School on Quantum Information Science, Kochi, Japan, September 2005
10. Invited talk at Yale University, New Haven, CT, September 2005
11. Invited talk at the Polar Molecules for Quantum Computing, Arlington, VA, September 2005
12. Invited talk on Control and Manipulation of Quantum Systems, Ascona Switzerland, Monte Verita 2005, July 2005
13. Invited talk at Quantum Communications Research Conference, Denver, CO, June 2005
14. Invited talk at Quantum Metrology MURI Kick-off, Boulder, CO, June 2005
15. Invited talk at Slow Light Darpa Meeting, Destin, FL, May 2005
16. Invited talk at Quantum Physics of Nature/QIPC 2005, Vienna, Austria, May 2005
17. Invited keynote talk, International Conference on Coherent and Nonlinear Optics, St. Petersburg, Russia, May 2005
18. Invited talk at the APS March Meeting, Los Angeles, CA, March 2005
19. Invited talk at the Gordon Research Conference: Quantum Information Science, Ventura, CA, March 2005
20. Invited talk at the French-Israeli Symposium on Non-Linear and Quantum Optics (Frisno-8), Ein Bokek, Israel, February 2005

21. Colloquium at the Weizmann Institute of Science, Rehovot, Israel, February 2005
22. Colloquium at Yale University, Department of Physics Colloquium, New Haven, CT, February 2005

2004

1. Invited talk at Quantum Information (QUIST) fall review, Scottsdale, AZ, November 2004
2. Colloquium at the University of Minnesota, Minneapolis, MN September 2004
3. Towards long-distance quantum communication using solid-state devices, , MURI review, McLean VA, September 2, 2004
4. Invited talk at DARPA Slow Light Kick-off meeting, Washington DC, August 2004
5. Stationary pulses of light in an atomic medium, Nonlinear Optics Topical Meeting, Waikoloa Hawaii, August 3, 2004
6. Shaping quantum pulses of light via coherent atomic memory, invited talk, Workshop on Coherent Spectroscopy and Quantum Information, Universidade Federal de Pernambuco, Recife, Brazil, July 21-23, 2004
7. Quantum Control of light using coherent atomic memory, International Conference on Atomic Physics, Rio de Janeiro, Brazil, July 29, 2004
8. Lecture series at the University of Boulder Summer School on quantum coherence in atomic and condensed matter systems, Boulder CO, July 2004
9. DARPA Conference on Quantum Information, Dr. Caspar van de Wal, Beverly Hills, CA, June 21-26, 2004
10. Invited talk at the Workshop on Coherent Control, University of Michigan, Ann Arbor, MI, June 2004
11. Atomic memory basics and applications, tutorial seminar to participants in the Teaching Opportunities in Physical Science program, MIT-Harvard Center for Ultracold Atoms, Cambridge, MA, June 31, 2004
12. Shaping quantum pulses of light via atomic memory, International Conference on Quantum Optics, Minsk, Belarus, May 30, 2004
13. Dark states as memory for quantum bits, Quantum Optics seminar, ETH, Zurich, Switzerland, May 27, 2004
14. Invited talk at the Division of atomic, molecular and optical physics conference, Tucson, AZ, May 2004
15. Quist 2004 Conference, poster presentation, Chicago, IL Matthew Eisaman, May 4-6, 2004
16. Physics Colloquium, JILA and Physics Department, University of Colorado, Boulder, CO, April 2004,
17. Towards quantum control of light: shaping quantum pulses of light via coherent atomic memory, QUACS Conference, Les Houches, France, April 26, 2004
18. Shaping quantum pulses of light via coherent atomic memory, MIT-Harvard Center for Ultracold Atoms weekly seminar, MIT, Cambridge, MA, April 13, 2004
19. Invited talk at the Physics Colloquium, Princeton University, Princeton, NJ, March 2004

20. Shaping quantum pulses of light via atomic memory, ITAMP, Cambridge MA, March 15, 2004
21. "Stationary pulses of light in an atomic medium", Conference on "Quantum Information with Atoms, Ions and Photons" La Thuile - Italy, Axel Andre. March 11, 2004
22. Stationary pulse in atomic vapor, Lebedev Institute of Physics, Moscow, Russia, January 2004

2003

1. "Stationary pulses of light in an atomic medium", DARPA Slow Light workshop, Orlando Florida, Axel Andre, December 2, 2003
2. Quist Fall Meeting, Prof. Mikhail Lukin, Ft. Lauderdale, FL, November 2003
3. Invited talk at the Packard Foundation Reunion, Vancouver, Canada, September 2003
4. Physics Colloquium, University of Toronto, Toronto, Canada, September 2003
5. Exploring new interfaces between quantum optics and condensed matter, Workshop on Theory in Quantum Computations, Harpers Ferry, WV, July 2003
6. Invited talk at the Gordon research conference on nonlinear optics, New London, NH, July 2003
7. Keynote talk at the European Quantum Electronics Conference, EQEC 2003, Munich, Germany, June 2003
8. Invited talk at the Gordon research conference on atomic physics, Tilton, NH, June 2003
9. Invited talk at the Quantum Electronics and Laser Science Conference, CLEO/QELS 2003, Baltimore, MD, June 2003
10. Invited talk at the APS meeting of Division of Atomic and Molecular Physics, DAMOP 2003, Boulder CO, May 2003
11. Invited talk at the Gordon research conference on quantum in formation, Ventura, CA, March 2003
12. Invited talk at the Innsbruck quantum optics conference, Obergurgl, Austria, February, 2003
13. “Chez Pierre” Condensed Matter Physics Seminar, MIT, Cambridge, MA February 2003
14. Atomic and Optical Physics Colloquium, University of Michigan, Ann Arbor, MI January 2003

2002

1. Invited talk at the MIT Workshop on Quantum Control, Cambridge, MA, October 2002,
2. Invited talk at the NSF workshop on new opportunities in materials theory, Wash., DC, October 2002
3. Invited talk at the annual meeting of OSA 2002, Orlando, FL, October. 2002
4. Invited talk at the New Laser Science Conference 2002, Orlando, FL, September 2002
5. Invited talk at the ARO/NSA/ARDA quantum computing program meeting, Nashville, TN, August 2002

6. Invited talk at the ICAP 2002, Cambridge, MA, August 2002
7. Invited talk at the IQEC 2002, Moscow, Russia, June 2002

(d) Manuscripts submitted, but not published

1. Novikova, A.V. Gorshkov, D.F. Phillips, A.S. Sorensen, M.D. Lukin, R.L. Walsworth, "Optimal control of light pulse storage and retrieval." quant-ph/0702266 (2007)
2. H.A. Engel, J.M. Taylor, M.D. Lukin, A. Imamoglu, "Quantum optical interface for gate-controlled spintronic devices," cond-mat/0512700, submitted to Phys. Rev.Lett (2006)
3. V. Gorshkov, A. Andre, M. D. Lukin, and A. S. Sorensen, "Photon storage in Lambda-type optically dense atomic media. I. Cavity model", e-print quant-ph/0612082, submitted to Phys.Rev.A (2006)
4. V. Gorshkov, A. Andre, M. D. Lukin, and A. S. Sorensen, "Photon storage in Lambda-type optically dense atomic media. II. Free space model", e-print quant-ph/0612083, submitted to Phys.Rev.A (2006)
5. V. Gorshkov, A. Andre, M. D. Lukin, and A. S. Sorensen, "Photon storage in Lambda-type optically dense atomic media. III. Effects of inhomogeneous broadening", e-print quant-ph/0612084, submitted to Phys.Rev.A (2006)
6. L. Jiang , J.M. Taylor, M.D.Lukin, "A fast and robust approach to long-distance quantum communication with atomic ensembles," quant-ph/0609236, submitted to Phys.Rev.A (2006)
7. A.V. Gorshkov, A. Andre, M.Fleischhauer, A.S. Sorensen, M.D. Lukin, "Optimal storage of photon states in optically dense atomic media," quant-ph/0604037, in press, Phys.Rev.Lett. (2006)
8. D.E. Chang, A.S. Sorensen, P.R. Hemmer, M.D. Lukin, "Strong coupling of single emitters to surface plasmons," quant-ph/0603221, submitted to Phys.Rev.B (2006)
9. D.E. Chang, A.S. Sorensen, P.R. Hemmer, M.D. Lukin, "Cavity quantum electrodynamics with surface plasmons," quant-ph/0506117 v1, submitted to Phys.Rev.Lett. (2005)
10. G. Giedke, J.M. Taylor, D. D'Alessandro, M.D. Lukin, A. Imamoglu, "Scheme for Quantum Measurement of the Nuclear Spin Polarization in Quantum Dots," quant-ph/0508144, submitted to Phys.Rev.A (2005)

(f) Book Chapter

1. L. Childress, M. Eisaman, A. Andre, F. Massou, A. Zibrov, M. Lukin, "Towards quantum control of light: shaping quantum pulses of light via coherent atomic memory" to be published in "Decoherence, Entanglement and Information Protection in Complex Quantum Systems," NATO Science Series Volume 2, Springer/Kluwer Academic (2005)

List of all participating scientific personnel

Note advanced degrees earned while employed on the project

Research Scientist
Alexander Zibrov

Postdoctoral Fellows
Ehud Altman
Vlatko Balic
Gurudev Dutt
Dimitry Petrov
Anatoli Polkovnikov
Andre Sorensen
Casper van der Wal
Philip Walther
Daw-wei Wang

Research Fellows
Tomasso Calarco
Ana Maria Rey

Graduate Students
Axel André, earned PhD, 2005
Michal Bajscy
Darrick Chang
Lilian Childress, earned PhD, 2006
Matthew Eisaman, earned PhD, 2006
Mohammad Hafezi
Michael Hohensee
Jiang Liang
Aryesh Mukherjee
Alex Nemiroski
Jacob Taylor, earned PhD, 2006
Emre Togan
Saijun Wu

Undergraduate Students
Florent Massou dit Labaquere
Sidharth Shenai

Long-term Participants
Philip Hemmer, Texas A&M University, professor
Mughees Khan, Texas A&M University, graduate student
Peter Zoller, University of Innsbruck

Subagreements

Smithsonian Astrophysical Observatory, Dr. Ronald Walsworth
Texas A&M University, Professor Philip Hemmer
Harvard University, Professor Charles Marcus

Honors 2002 to the present

Alfred P. Sloan Fellowship (2003)
From the Alfred P. Sloan Foundation
$40,000

David and Lucille Packard Foundation Award for Science and Engineering (2002)
From the David and Lucille Packard Foundation
$625,000

Career: Coherence and quantum control of strongly interacting systems (2002)
National Science Foundation
$716,911

AAAS Newcomb Cleveland Prize (2006)
Advancing Science Serving Society

Other Sponsored Work

Funding Agency: NSF
Status: Awarded
Title: CAREER: Coherence and quantum control of strongly interacting systems
Funds awarded: $716,911
Period of Performance: 8/1/2002 – 7/31/2009

Funding Agency: David and Lucile Packard Foundation
Status: Awarded
Title: *David and Lucile Packard Foundation Award for Science and Engineering*
Funds awarded: $625,000
Period of Performance: 9/1/2002 – 8/31/2007

Funding Agency: Stanford University/ARO/MURI
Status: Awarded
Title: *Photonic Quantum Information Systems*
Funds awarded to PI: $476,679
Period of Performance: 7/1/2003 - 6/30/2008

Funding Agency: California Institute of Technology/ONR/MURI
Status: Awarded
Title: *Quantum Metrology with Atomic Systems: Principles and Implementations*
Funds awarded to PI: $244,038
Period of Performance: 5/1/2005 – 6/30/2008

Funding Agency: Army Research Office
Status: Pending approval of revised budget
Title: *STIC: Long-range Coupling of Solid-state Qubits for Scalable Quantum Computation*
Funds requested: $650,000 (Prof. Lukin's part of)
Period of Performance: 8/15/2005 – 8/14/2008

Funding Agency: Air Force Office of Scientific Research/DARPA
Status: Awarded
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